Specification

METHOD FOR MAKING JUNCTION AND PROCESSED MATERIAL FORMED

USING THE SAME

5   <Technical Field>

This invention relates to a method for making a junction and a processed material formed using the same, and more particularly to a method for making a junction for forming an electronic device on a semiconductor substrate and a method for making a junction for forming an electronic device

10   on a substrate on which a semiconductor thin film is formed on an insulating substrate surface, which is used for a liquid crystal panel.

<Background Art>

For example, in forming device regions in a semiconductor substrate, a

15   large number of pn junctions are used.   An SOI (silicon on insulator) with a silicon thin film formed on a substrate surface through an insulating film has been widely employed for several semiconductor devices such as DRAM. Further, a glass substrate with a semiconductor thin film formed on a substrate surface is widely noticed by attempting miniaturization and high speed of a

20   liquid crystal panel through integration of a driving circuit of liquid crystal including a thin film transistor (TFT) in the semiconductor thin film.

As described above, in forming various semiconductor devices, pn junctions are employed.   In order to form these pn junctions, traditionally, a method has been adopted in which after p-type impurities such as boron are

25   introduced in an n-type Si substrate thorough ion implantation, they are

1

electrically activated by a halogen lamp.

For example, as a method for introducing boron that is the p-type impurities, in addition to the ion implantation, plasma doping is expected as a next-generation method capable of effectively introducing particles with very

5   low energy.

As a method for electronically activating the ions such as the boron ions introduced, a method for applying xenon flash lamp light, entire-solid laser light or excimer laser light in addition to halogen lamp light has been researched and developed.

10   All the xenon flash lamp light, solid laser light and excimer laser light have an intensity peak at a shorter wavelength than the halogen lamplight. For example, the conventional halogen lamp light has the intensity peak at 1000-1100 nm, whereas the xenon lamp light has the intensity peak at the wavelength of 400-500 nm and the excimer laser light has the intensity peak at

15   the wavelength of 400 nm or less. Since they have the peak at a shorter wavelength, they can be effectively absorbed in silicon(Si) (see Non-patent References 1 and 2). Thus, by absorbing light energy at a shallow portion in a substrate surface, a shallow activated layer can be formed.

Further, a method has been also proposed for forming a shallow

20   activated layer using a difference in a light absorption coefficient between silicon crystal and amorphous silicon. Specifically, in a wavelength range of 375 nm or longer, the amorphous silicon has a larger light absorption efficient than the silicon crystal. Thus, an amorphous layer is previously formed on a Si substrate surface before irradiated with light, and thereafter light is applied to

25   cause the amorphous layer to absorb more light energy, thereby making a

2

shallow activated layer. The amorphous layer is formed by ion-implanting e.g. germanium (see Non-patent References 1, 2, 3, 4 and 5).

By these research researches, a result has been reported in which the light with a shorter wavelength ranging from 375 nm (inclusive) to 800 nm
5 (inclusive) is applied to cause the substrate to effectively absorb the light energy, thereby making a shallow junction (see Non-patent References 1 and 2). In these reports, generally, prior to introduction of impurities, the substrate surface is previously changed to be amorphous and thereafter the impurities are introduced. In this case, for impurity introduction, ion-implantation of BF^{2+}
10 or B^+ is adopted and for previous amorphous-changing, ion-implantation of germanium or silicon is adopted. Namely, ion implantation must be twice carried out. This led to a problem that the process is complicated. Further, in order to make the shallow junction, in the case of ion-implantation of BF^{2+} or B^+, an accelerating voltage must be lowered to several hundreds V so that the
15 beam current value is lowered. This led to a problem of low throughput. Furthermore, since there are many combinations of twice-ion-implantation conditions and the methods for introduction and electronic activation of boron are often individually researched and developed, under present circumstances, the state of the substrate surface suitable to the wavelength of an
20 electromagnetic wave to be applied is not still known.

Non-patent Reference 1: Ext. Abstr. of IWJT, pp23-26, Tokyo, 2002.

Non-patent Reference 2: Symposium on VLSI Technology Digest of Technical Papers, pp53-54, Kyoto, 2003.

Non-patent Reference 3: Ext. Abstr. of IWJT, pp31-34, Tokyo, 2002.
25 Non-patent Reference 4: Ext. Abstr. of IWJT, pp27-28, Tokyo, 2002.

3

Non-patent Reference 5: 2000 International Conference on Ion Implantation Technology Proceedings, 2000, pp.175-177.

<Disclosure of the Invention>

5   In a method for making a junction in which after impurities have been introduced in a solid substrate such as a Si substrate, they are electrically activated by application of an electromagnetic wave, for impurity introduction, ion-implantation of BF^{2+} or B^+ is adopted and for previous amorphous-changing, ion-implantation of germanium or silicon is adopted. In this case, ion

10 implantation must be twice carried out. This led to a problem that the process is complicated. Further, in order to make the shallow junction, in the case of ion-implantation of BF^{2+} or B^+, an accelerating voltage must be lowered to several hundreds V so that the beam current value is lowered. This led to a problem of low throughput. Furthermore, since there are many combinations

15 of twice-ion-implantation conditions and for other reasons, the state of the substrate surface suitable to the wavelength of an electromagnetic wave to be applied is not still known. The method for making the substrate surface adapted to the electromagnetic wave to be applied is not still established.

      Under such a circumstance, a method for making the state of the

20 substrate surface adapted to the wavelength of the electromagnetic wave to be applied, which is simple in the process, and high in the throughput as compared with conventional ion implantation, has been demanded.

      This invention has been accomplished in view of the above circumstances. An object of this invention is to provide a method for making a

25 junction which can make a shallow junction with high accuracy and high

4

throughput through a simple process.

In order to attain the above object, in the method according to this invention, the suitable state of a substrate surface adapted to the wavelength of light (electromagnetic wave) to be applied is formed, and thereafter the light (electromagnetic wave) is applied to electrically activate the impurities.

The inventors of this invention found that the light absorption coefficient, reflectivity, absorptance of light and the thickness of a doped layer can be adjusted by changing a plasma condition through the experiments of repeating the creation of samples in which boron is introduced in a Si substrate with changed conditions of plasma doping and evaluation of the optical property of each the sample surfaces using an ellipsometer. Further, the inventors also theoretically found that the plasma condition and light to be applied to electrically activate the boron can be appropriately combined so that the sample effectively absorbs the light to electrically activate the impurities introduced at a high rate, the layer containing the boron is selectively excited to preferably activate the boron within the layer, and the impurities are prevented from being diffused at a deep position of the Si substrate. This invention has been accomplished paying attention to this point.

This invention provides a method for making a junction in which after impurities have been introduced in a solid substrate of Si, an electromagnetic wave is applied to activate the impurities, characterized in that He plasma is applied before the electromagnetic wave is applied. This is because the light absorptance of the Si substrate surface for the light ranging from 375 nm to 800 nm is greatly improved by applying the He plasma. In place of the He plasma, Ar plasma may be adopted. Otherwise, the plasma containing the element to

be impurities diluted with He or Ar can also provide the same effect.

Namely, the method for making a junction includes the steps of:

forming, on the surface of a semiconductor substrate, a thin film containing an element that can be electrically activated within the

5   semiconductor substrate; and

applying light having an intensity peak at a wavelength longer than 375 nm (inclusive) on the semiconductor substrate so that the thin film is selectively excited thereby to electrically activate the element within the thin film.

Now, it is assumed that the "light" means the light in the broad sense

10   inclusive of an electromagnetic wave.   The energy for selective excitation is not desired to have a narrow band like laser, and is desired to be the light not having directivity.   This is because the high light absorptance of the thin film for the wavelength over a wide range can be effectively employed.   In contrast, the narrow band energy like the laser employs the absorptance for a specific

15   wavelength of the thin film.

Further, the laser can be applied to only a small area because of its limitative output.   Therefore where it is desired that the energy is applied to a relatively larger area like e.g. 1 cm x 1 cm or more to process the product, the method of scanning is adopted.   This requires dealing with the manufacturing

20   shortcoming of limited throughput.   On the other hand, a halogen lamp or xenon lamp, which can apply the light over a wide range of wavelength onto a large area, does not give rise the above problem and hence is desirable.

Incidentally, the thin film containing the element which can be electrically activated is generally formed through modification by plasma doping

25   for the semiconductor substrate. Otherwise, it is formed through modification by

6

plasma doping for the semiconductor substrate and also by doping the element which can be electrically activated within the semiconductor substrate. Further, it may be also formed by making deposit on the surface of the semiconductor substrate.

5   For example, the thin film containing the element which can be electrically activated within the semiconductor substrate may be formed after the surface of the semiconductor substrate has been made amorphous by plasma application. Otherwise, the thin film containing the element which can be electrically activated within the semiconductor substrate may be formed by

10   making the surface of the semiconductor substrate amorphous by plasma application after the element which can be electrically activated has been introduced in the semiconductor substrate.

In the method for making a junction, preferably, the light applying step satisfies at least one of conditions that with respect to the light absorptance of

15   the thin film, assuming that the wavelength is λ(nm) and the absorptance is A(%), at the wavelength ranging from 375 nm (inclusive) to 500 nm, A > $7E32\lambda^{-12.316}$; at the wavelength ranging from 500 nm (inclusive) to 600 nm, A > $2E19\lambda^{-7.278}$; at the wavelength ranging from 600 nm (inclusive) to 700 nm, A > $4E14\lambda^{-5.5849}$; and at the wavelength ranging from 700 nm (inclusive) to 800 nm,

20   A > $2E12\lambda^{-4.7773}$.

In the method for making a junction according to this invention, preferably, the light applying step satisfies at least one of conditions that with respect to the light absorption coefficient of the thin film, assuming that the wavelength is λ(nm) and the absorption coefficient is α (cm^{-1}), at the

25   wavelength ranging from 375 nm (inclusive) to 500 nm, α > $1E38\lambda^{-12.505}$; at the

wavelength ranging from 500 nm (inclusive) to 600 nm, $\alpha > 1E24\lambda^{-7.2684}$; at the

wavelength ranging from 600 nm (inclusive) to 700 nm, $\alpha > 2E19\lambda^{-5.5873}$; and

at the wavelength ranging from 700 nm (inclusive) to 800 nm, $\alpha >$

$1E17\lambda^{-4.7782}$.

5   In these methods, since the absorptance can computed according to

the wavelength for application on the basis of several kinds of experimental

results, the thin film can be effectively annealed.

Further, in the method for making a junction according to this invention,

preferably, the semiconductor substrate is an n-type silicon (Si) substrate, and

10   the impurity is boron to be supplied to the surface of the Si substrate.

Further, in the method for making a junction according to this invention

comprising the steps of: introducing boron as impurities in an n-Si(100)

substrate and an n-Si (100) substrate with a plane inclined by several degrees

by plasma doping; and applying laser light from 375 nm (inclusive) to 800 nm

15   (inclusive) to the boron-introduced n-Si(100) substrate so that the boron is

electrically activated, preferably, the boron-introduced n-Si(100) substrate has a

light absorptance of $A > 1E19\lambda^{-6.833}$ for the light from 375 nm (inclusive) to 800

nm(inclusive).

In the method for making a junction according to this invention

20   comprising the steps of: introducing boron as impurities in an n-Si(100)

substrate and an n-Si (100) substrate with a plane inclined by several degrees

by plasma doping; and applying laser light from 375 nm (inclusive) to 800 nm

(inclusive) to the boron-introduced n-Si(100) substrate with so that the boron is

electrically activated, preferably, the boron-introduced n-Si(100) substrate has a

25   light absorptance of $A > 1E19\lambda^{-7.1693}$ for the light from 375 nm (inclusive) to 800

nm(inclusive).

Further, in the method for making a junction according to this invention, the impurity introducing step is to apply plasma containing boron diluted with He to the n-Si(100) substrate and n-Si (100) substrate with a plane inclined by several degrees, for its plasma doping.

5

Further, in the method for making a junction according to this invention, preferably, the light absorption coefficient is measured by an ellipsometer with an incident angle of 70 degrees for a three-layer structure consisting of air, the thin film (boron-introduced layer) and the semiconductor substrate.

10

Further, in the method for making a junction according to this invention, preferably, after the light absorption coefficient and the thickness of the boron-introduced layer have been measured by an ellipsometer with an incident angle of 70 degrees for a three-layer structure consisting of air, the thin film and the semiconductor substrate, assuming that the thickness of the boron-introduced layer is D (cm), the light absorptance is computed as A = 100x(1-exp(-α·D)).

15

Further, in the method for making a junction according to this invention, prior to the application of the electromagnetic wave, carried out is a combination of steps of applying He plasma, Ar plasma, plasma containing He or plasma containing Ar to the semiconductor substrate, and applying the plasma containing particles serving as impurities to the solid substrate, for its plasma doping. For example, preferably, after the Si substrate has been irradiated with the He plasma, plasma doping is carried out with the plasma containing boron. Otherwise, after the plasma doping by the plasma containing boron, the Si substrate may be irradiated with the He plasma.

20

25

In accordance with this invention, the light absorption coefficient can be tested through the measurement using an ellipsometer with an incident angle of 70 degrees for a three-layer structure consisting of air, the boron-introduced layer and the semiconductor substrate. Further, after the light absorption

5 coefficient and the thickness of the boron-introduced layer have been measured by an ellipsometer with an incident angle of 70 degrees for a three-layer structure consisting of air, the boron-introduced layer and the semiconductor substrate, assuming that the thickness of the boron-introduced layer is D (cm), the light absorptance can be computed as A =

10 $100 \times (1-\exp(-\alpha \cdot D))$.

This invention satisfies the condition of the absorption coefficient so that the boron is effectively activated, thereby permitting a shallow junction to be effectively formed.

It is also effective to replace the n-Si(100) substrate by the

15 semiconductor thin film formed on an SOI substrate, a distorted Si substrate or a glass substrate.

Further, the semiconductor device manufactured by the above method for making a junction or the electronic element such as a liquid-crystal substrate made using it are also effective.

20 Further, in this invention, in the above method for making a junction, the optical property of the substrate may be detected by ellipsometry or XPS.

Further, in this invention, in the above method for making a junction, the plasma doping step includes to control at least one of a power source voltage applied to plasma, plasma composition or ration between the time of plasma

25 application containing the dopant material and the time of plasma application

not containing the dopant material.

By this method, the control can be effectively carried out. In this case, the plasma composition is controlled by adjusting the mixing ratio between the impurity substance serving as the dopant and other substances, vacuum

5   degree, mixing ratio between the other substances, etc.

Further, in this invention, in the method for manufacturing the substrate, the plasma doping step includes a step of controlling the optical property of the impurity-introduced region by changing the mixing ratio between the impurity substance and the inert substance or reactive substance serving as the

10   substance to be mixed with the impurity substance. In this case, the optical property is controlled by changing the ratio between the impurity substance such as arsenic, phosphorus, boron, aluminum, antimony or indium and the inert substance such as helium, argon, xenon or nitrogen or reactive substance such as oxygen, silane or disilane, serving as the substance to be mixed with

15   the impurity substance.

Further, in the method for making a junction according to this invention, preferably, the plasma doping step sets the optical constant of the impurity-introduced region so that in the annealing step, the electrical activation of the impurities contained in the impurity-introduced region is promoted and

20   the energy absorption in the substrate is suppressed.

By this method, the annealing can be realized selectively and effectively without rising the substrate temperature.

In this case, the energy applied for the annealing may be not only the light energy but also may be the electromagnetic wave in the broad sense.

25   The light source may be not only the halogen lamp light such as the xenon flash

11

lamp but also white light, entire-solid laser light or excimer laser light.

All the xenon flash lamp light, solid laser light and excimer laser light have an intensity peak at a wavelength shorter than the halogen lamp light. For example, a conventional tungsten halogen lamp light has an intensity peak

5   at 1000 to 1100 nm, whereas the xenon flash lamp light and the excimer laser light have an intensity peak at the wavelength of 400 to 500 nm and at 400 nm or less, respectively.   These kinds of light has the intensity peak at the shorter wavelength so that the light can be effectively absorbed in Si (see Non-patent references 1 and 2).   Thus, the light energy can be absorbed at a shallow

10   portion in the substrate surface so that a shallow activated layer can be formed.

It should be noted that the impurity introducing step, as concretely described in the following embodiment, is not only simply introducing impurities, but in the annealing step

of mainly light application subsequently executed, simultaneously or

15   sequentially supplying the impurity substance, the inert substance such as inert gas or nitrogen and reactive substance such as oxygen, silane or disilane in their combination so that energy can be effectively absorbed, thereby setting the optical property optimum to the annealing step.   The impurity introducing step in this invention refers to the above series of steps.

20   Further, in this invention, the light applying step can be replaced by the step of applying the electromagnetic wave.   The addition of the electromagnetic component permits the annealing to be selectively carried out more effectively within the thin film.

As described above, in accordance with this invention, the state of the

25   substrate surface is adjusted in terms of the thickness, impurity concentration,

12

etc. according to the theoretical value based on the wavelength so as to facilitate the activation of impurities such as boron so that the annealing can be effectively carried out. Namely, since the impurities are effectively activated in the region where the impurities exist, the impurity elements existing within the

5   semiconductor thin film or contiguous thereto are effectively diffused in the semiconductor thin film and so can be effectively activated, thereby effectively making the junction at the shallow position.

Thus, it is possible to provide a method for making a junction which is simple in the process and high in the throughput, and applies an

10   electromagnetic wave to electrically activate impurities after the suitable state of the substrate surface adapted to the wavelength of the electromagnetic wave to be applied has been prepared.

<Brief Description of the Drawings>

15   Fig. 1 is a view showing a substrate according to an embodiment of this invention.

Fig. 2 is a view showing a doping apparatus for making a junction according to an embodiment of this invention.

Fig. 3 is a graph showing exemplary combinations of the optical

20   property of a doped layer and a light intensity distribution according to an example of this invention.

Fig. 4 is a graph showing each of the doped layers according to an example of this invention and a comparative example.

Incidentally, reference numeral 100 denotes a semiconductor substrate;

25   110 an impurity thin film; 200 a vacuum chamber; 210 a vacuum pump; 230 a

13

vacuum meter; 240 a plasma source; 250 a power source; 260 a substrate holder; 270 a power source; 280 a line for supplying a dopant substance; 290 a line for supplying another substance 1; 200 a line for supplying another substance 2; 310 plasma; and 410 a photometer.

5

<Best Mode for Carrying Out the Invention>

Next, an explanation will be given of various embodiments of this invention.

Now, by detecting the state of a substrate having a thin film with

10   introduced impurities through optical measurement, it can be placed in a status optimum for activation. This means that not only are optically measured the impurities themselves, but also the substrate state is optically measured as that of a composite layer inclusive of the crystalline state of the thin film itself, physical change in the crystalline state of the thin film such as the damage due

15   to energy in introduction and chemical change in the thin film such as creation of an oxide layer or nitride layer.

(Embodiment 1)

In the first embodiment, the basic construction of a substrate will be

20   explained. As seen from Fig. 1, on an n-Si (100) substrate 100 is formed an impurity thin film 110 containing as a main component the impurities which can be carriers when electrically activated within the substrate.

Namely, the impurity thin film 110 is formed of an amorphous thin film containing a large quantity of lattice defects.

25   This state can be obtained, for example by introducing impurities in a

14

semiconductor substrate using particles with energy (several 10 eV or more) sufficiently higher than the binding energy of lattices.   Where the particles with energy (several 10 eV or more) sufficiently higher than the binding energy of lattices are used in order to introduce the impurities in the semiconductor thin

5   film, the physical property of the semiconductor thin film will be changed owing to the creation of the lattice defects for the lattices of the crystalline or amorphous substance which constitutes the semiconductor substrate or the semiconductor thin film formed thereon and owing to the impurity substance itself.   Thus, the impurity thin film 110 having the physical property different

10   from the essential semiconductor substrate or the semiconductor thin film will be formed.   Further, in this case, the lattice defects are introduced into the semiconductor substrate 100 itself so that the semiconductor substrate is placed in the status changed from its inherent physical property.

First, an explanation will be given of a plasma doping apparatus serving

15   as a plasma CVD apparatus employed in this embodiment.   The doping apparatus employed in this embodiment, as seen from Fig. 2, is used to introduce impurities in the semiconductor substrate 100 to form the impurity thin film 110.

Now, this apparatus includes a light source 400 and a photometer 410

20   which serve as a measuring means for measuring the optical property of the semiconductor substrate 100 on the surface of which the impurity thin film 110 with the introduced impurities is formed as described later, and a control means for controlling the doping condition on the basis of the optical property obtained by the measuring means, thereby feedback-controlling the doping condition to

25   provide an optimum surface status.

Specifically, the plasma doping apparatus includes a vacuum chamber 200 and a plasma source 240 for creating plasma with the vacuum chamber 200, thereby performing plasma doping for the surface of the semiconductor substrate 100 placed on a substrate holder 260 and serving as a substrate to

5   be processed.

And the vacuum chamber 200 is connected to a vacuum pump 210 and to a vacuum meter 230 for vacuum measurement. The plasma source 240 is connected to a power source 240. The substrate holder 260 is connected to a power source 270 for applying an individual electrical potential, which are

10   separated from the above power sources.

The vacuum chamber 200 is provided with a gas introducing mechanism for introducing these gases. This gas introducing mechanism consists of a first line 280 for supplying a first substance serving as a dopant substance, a second line 290 for supplying a second substance which is

15   another substance (in this embodiment, He) and a third line 300 for supplying a third substance which is still another substance (in this embodiment, Ar).

Further, as required, the plasma doping apparatus may include a control apparatus consisting of a computer 320 for computing the optical property measured by the photometer 410, a control circuit 340 for determining

20   the control condition on the basis of the computed result and a controller 350 for feedback-controlling the doping condition of the plasma doping apparatus on the basis of an output from the control circuit 340.

First, with the vacuum chamber adjusted to a predetermined pressure, a gas is supplied by an ordinary manner to create plasma and perform doping.

25   Now, an explanation will be given of the case using the gas as a doping

16

source.

First, the dopant substance serving as a first gas is supplied into the
vacuum chamber 200.   In this case, in addition to the dopant substance, the
other substance different therefrom serving as a carrier gas or having a
5   particular function is also introduced.   In this embodiment, the gas different
from the dopant substance in their property, such as inert gas (different in the
mass) or substance not electrically activated within Si was selected.
Examples of such a gas are He and Ar.   In this embodiment, as the other
second substance, He was selected, and as the third substance, Ar was
10   selected.   From the gas introducing lines consisting of the above first to third
lines 280, 290 and 300, the gases are introduced to generate plasma 310 on
the surface of the solid substrate 100 located within the vacuum chamber 200.

.Owing to an electrical potential difference between the plasma 310 and
the semiconductor substrate 100 surface, charged particles in the plasma are
15   attracted to perform the impurity doping.   Simultaneously, an electrically
neutral substance within the plasma is applied or occluded in the vicinity of the
surface of the solid substrate 100.   In this case, the surface status depends on
the status of the semiconductor substrate 100 which is an underlying material
and the energy of the plasma in the applied or occluded state.   Now, the above
20   electrically neutral substance is occluded in the semiconductor substrate 100
and also applied to the surface of the semiconductor substrate 100 so as to
form an impurity thin film.

By this impurity doping step, the impurity introduced layer 110
explained in the above embodiment is formed on the semiconductor substrate
25   100 surface.   Desirably, in order to measure the physical property of the

17

impurity introduced layer, the vacuum chamber 200 incorporates the light source 400 and the photometer 410. And the optical property measured by the photometer 410 is operated by the computer 320; the operated result is sent to the control circuit 340; and the data are sent to the controller 350 as feedback information. Thus, the plasma doping apparatus adjusts the plasma condition to control the physical property of the impurity introduced layer.

The plasma condition to be adjusted includes a power source voltage to be applied to the plasma or voltage applying time and timing, mixing ratio between the dopant substance and other substances, vacuum degree, mixing ratio between the other substances, ratio between the application time of the plasma containing the plasma and that of the plasma not containing the plasma, etc. By changing these parameters, the physical property of the impurity introduced layer is controlled.

By performing the doping for the semiconductor substrate 100 with a sufficiently low electrical potential difference, e.g. 20 eV, the impurity thin film layer is formed on the semiconductor substrate 100.

On the other hand, by performing the doping for the semiconductor substrate 100 with a sufficiently high electrical potential difference, e.g. 200 eV, if the plasma containing a large quantity of impurities is in direct contact with the semiconductor thin film, ions with sufficiently high energy invade the semiconductor thin film surface, thereby forming the impurity thin film 110 which is the impurity introduced layer on the surface of the semiconductor substrate 100. Where the carrier gas is employed, the ions in the plasma of the carrier gas also invade the semiconductor thin film surface and are mixed with the impurities while breaking the crystals, thereby forming a mixture layer of an

amorphous semiconductor layer and a boron layer. Thereafter, if the concentration of the impurity, e.g. boron on the mixture layer exceeds the saturated quantity containable in the mixture layer surface, an amorphous boron thin film (impurity thin film) is formed.

5   Fig. 3 shows a light intensity distribution of applied light and a distribution of the light absorption coefficient of the substrate according to an example of this embodiment. The applied light is xenon flash light. The xenon flash light has an intensity peak at the wavelength in the vicinity of 470 nm as indicated by curve $\underline{a}$. Now, the light is illustrated as the light having the

10   intensity peak at the wavelength ranging from 375 nm to 800 nm.

In Fig. 3, the curve indicated by PD-1 exhibits the absorption coefficient of the light after the n-Si(100) substrate has been plasma-doped with boron. The introduction of boron in PD-1 was carried out by plasma-doping so that the n-Si(100) substrate was irradiated with the plasma containing boron diluted with

15   He. The doping time was 60 sec. The same result was obtained by the doping for 7 sec or 30 sec. As regards the light absorption coefficient of the boron introduced layer in PD-1, assuming that the wavelength is λ(nm) and the absorption coefficient is α (cm^{-1}), at the wavelength ranging from 375 nm (inclusive) to 500 nm, $\alpha > 1E38\lambda^{-12.505}$; at the wavelength ranging from 500

20   nm (inclusive) to 600 nm, $\alpha > 1E24\lambda^{-7.2684}$; at the wavelength ranging from 600 nm (inclusive) to 700 nm, $\alpha > 2E19\lambda^{-5.5873}$; and at the wavelength ranging from 700 nm (inclusive) to 800 nm, $\alpha > 1E17\lambda^{-4.7782}$. As seen from Fig. 3, it can be understood that PD-1 after the plasma doping has been performed exhibits a higher light absorption coefficient for the xenon flash lamp light than

25   the n-Si(100) substrate.

The curve indicated by PD-2 in Fig. 3 exhibits the light absorption coefficient when the plasma doping was performed under a condition different from in PD-1. The doping time was 30 sec. PD-2 exhibited a higher light absorption coefficient than the n-Si(100) substrate and PD-1.

5   Fig. 4 shows the distribution of the light absorption coefficient of the substrate according to an example of the embodiment of this invention when the light to be applied is laser light. Where the applied light has a single wavelength like the laser light, as compared with the light having the intensity distribution for the wavelength, it is required to set a larger difference in the light

10   absorption coefficient between the doped layer and the n-Si(100). PD-3 exhibits the curve of the light absorption coefficient of the doped layer which was formed to be adapted to the laser at the wavelength of 500 to 550 nm by adjusting the doping condition. Where the absorption coefficient is smaller than this curve, boron was diffused deeply after laser annealing. Namely, only

15   if the light absorption coefficient of the boron introduced layer for the light from 375 nm (inclusive) to 800 nm (inclusive) is $\alpha > 1E24\lambda^{-7.1693}$, boron could be electrically activated without changing the depth distribution of boron. This may be attributable to the fact that where the absorption coefficient is smaller than the curve by PD-3 in Fig. 3, the laser energy cannot be sufficiently

20   absorbed by the surface doped layer so that the rate of the energy absorption in the silicon substrate below the doped layer is high.

Now referring to Table 1, the diffusion depth of boron in examples will be explained. It is assumed that the diffusion depth is represented by the depth that provides the boron concentration of $1E18cm^{-3}$ and denoted by Xj.

25   The difference between Xj after doping and Xj after light application is denoted

by ΔXj.   Example A represents a combination of the steps of plasma doping of PD-1 and application of the light having an intensity peak at the wavelength ranging from 375 nm (inclusive) to 800 nm (inclusive) and an intensity distribution for the wavelength.   In this case, ΔXj ranges from several nm to 4 nm (inclusive).   Assuming that the average value of ΔXj at this time is 1, ΔXj of the other samples are normalized.   Example B represents a combination of plasma doping of PD-3 and application of the laser light at the wavelength ranging from 375 nm (inclusive) to 800 nm (inclusive).   In this case, ΔXj is similar to that in Example A, and the ΔXj ratio is 0.9.

(Table 1)

	Example A	Example B	Comparative Example
ΔXj Ratio	1.0	0.9	10

As described above, by performing the plasma doping, the doped layer having a higher light absorption coefficient than n-Si(100) can be easily formed by a single step.   In addition, by appropriately selecting the optical property of the doped layer and applied light, boron can be electrically activated without generally changing Xj, thereby making a shallow junction with high performance. In this case, by the condition of the plasma doping, the optical property of the doped layer can be easily adjusted.

Next, a comparative example will be explained.

Referring to Table 1, an explanation will be given of the difference in the diffusion depth between the examples according to this invention and the comparative example.   A sample in which the light absorption coefficient of the doped layer after boron has been introduced by plasma doping is PD-1 was

21

irradiated with the laser having an intensity peak at the wavelength ranging from 375 nm (inclusive) to 800 nm (inclusive). Namely, the comparative example is an combination of the plasma doping in PD-1 and the laser having an intensity peak at the wavelength ranging from 375 nm (inclusive) to 800 nm

5   (inclusive). In the sample subjected to the plasma doping by PD-1, the light energy absorbed by the PD (plasma-doped) layer is smaller by about one order of magnitude than in the sample by PD-2. Thus, the substrate deeper than the PD layer, now, e.g. n-Si(100) absorbs a higher rate of light. Since the light absorption coefficient of n-Si(100) is small, the light energy reaches a deep

10   range. Namely, boron diffuses deeply. In comparison of ΔXj, example A is 1 whereas the comparative example is 10 or so. Namely, in the comparative example, boron diffuses deeply by one order of magnitude than in the examples, and so apparently the shallow junction that is a target cannot be formed.

Additionally, in the embodiment described above, the explanation was

15   given of the method for making a shallow pn junction by forming the boron diffused layer in the n-Si(100) substrate. However, the substrate should not be limited to the n-Si(100), but may be a substrate inclined by several degrees. Further, it is needless to say that the conduction type of the impurities may be changed. Furthermore, with a suppressed temperature rise, the junction may

20   be formed in compound semiconductor also. Accordingly, the pn junction with a reduced change in the junction level and with high reliability can be made.

This invention has been explained in detail and with reference to the specific embodiment. However, it is apparent to those skilled in the art that this invention can be realized in various changes and modifications without

25   departing from the sprit and scope of this invention.

22

This application is based on Japanese Patent Application No. 2003-350368 filed in October 9, 2003, and the contents thereof is incorporated herein by reference.

5   <Industrial Applicability>

As understood from the description hitherto made, in accordance with this invention, after the suitable state of a substrate surface adapted to the wavelength of an applied electromagnetic wave has been formed, the electromagnetic wave is applied to electrically activate impurities. For this

10   reason, the process is simple, the throughput is high and the shallow junction can be easily formed. The method according to this invention is effectively employed to fabricate a miniaturized semiconductor integrated circuit.